Role of NDI in ABDR Assessment, Equipment & Logistics

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ABSTRACT

Use of Non Destructive Testing (NDT) technique during aircraft maintenance operations is increasing in the last years as well as the tools to perform these inspections are widening their field of application. Damage tolerance design approach has been selected by aeronautic industry for the last years also thanking to the most modern NDT capabilities, like ultrasound and thermography, which have been showing more and more reliable results. Whenever a safe life criterion has been applied, NDT are currently used to verify structural integrity of components in case of special events (heavy landing, bird strike, hail, tools drop, etc.) and to assess and monitorize quality and effectiveness of repairs and for rework.
This kind of approach can be very helpful especially in the case of composite materials damage assessment and also in the first line of Defense when a damage tolerance approach needs to be used in order to face spares unavailability or operational readiness and when a rapid and full understanding of damage extension and repairable area is highly required.
This paper deals with NDT techniques applicable for battle damage assessment, particularly focusing on composite airframe inspections, showing advantages/disadvantages of each method in ABDR context.
Case studies carrying out during research activities will be illustrated, showing results of NDT techniques applied on composite material structures.

1. INTRODUCTION

Damage assessment is one of the most important step during ABDR procedures application. Although ABDR/ABDAR manuals do not generally provide description of how performing damage assessment, this phase is critical and naked eyes inspections are usually not enough accurate to correctly define damage extension and depth. Hence NDT can be a useful tool to improve inspection capability, playing a key role also during repair assessment especially in the case of bonded patches, adhesive tape or co-cured laminates applications (figure 1).

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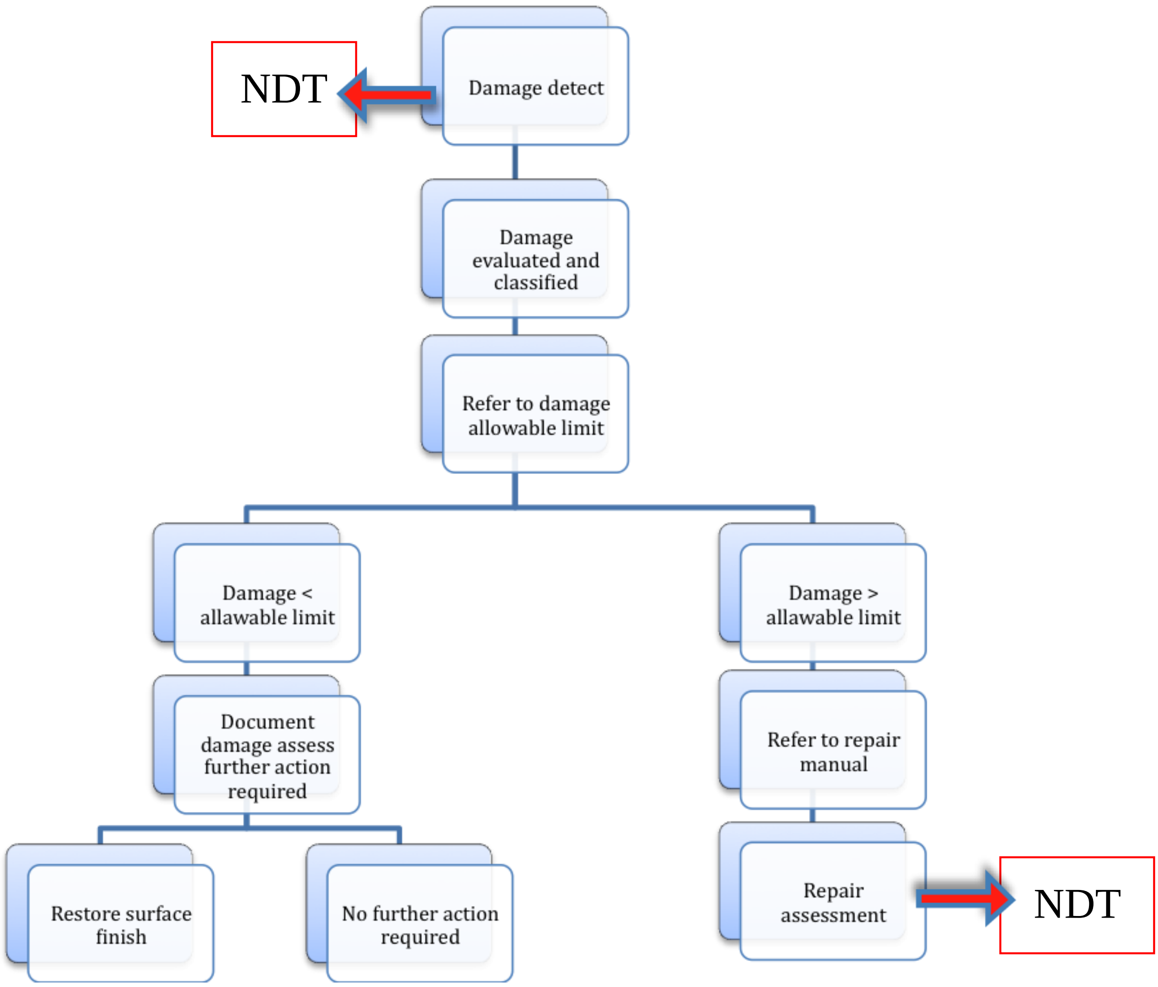


Figure 1

2. DAMAGE ASSESSMENT ON COMPOSITE STRUCTURES

Damage is defined as an irreversible change of an aircraft component due to an external load or to an unexpected event that in a certain way deforms the original shape or integrity. These events can be classified as mechanical actions (dropped tools, accidental knocks, battle damage, lightning strike), thermal/chemical actions, etc.

Damage is allowable if it does not affect integrity or functionality of the part. The boundary of allowable damages must be clear and in this context it is fundamental to apply the proper NDT technique in order to define as more exactly as possible the damage entity. The role of NDT is also more important when the structures are made of composite materials, like thermosetting based fiber metal laminates (FML), such as GLARE, or carbon/glass fiber-reinforced polymers (C/GFRP) where defects are often hidden inside bulk material and fracture mechanics is very different from metals.

The percentage of composites used in civil aircraft structures has been increasing over the time to reach the 100% in new Beech Starship, the first certified general aviation aircraft that has the structure entirely made of composite, and the same trend has been seen for Military Aircrafts. In

Italian Air Force (IAF) the percentage of composite materials is increasing from 16% for the tactical bomber AMX made of carbon fiber mainly at the horizontal and vertical stabilizer to 60% for the EFA Typhoon. In the case of EFA the primary and the secondary structure have been made of CFRPs and about 80% of the outer surface has been built of composite materials. Carbon fiber is used for wings, fin, rudder and a great part of the fuselage. In particular there is a great usage of laminates, co-cured and co-bonded stiffening elements such as j-spar, web etc. Nowadays the most modern military aircrafts, such as F-35, make heavy use of composite materials. As a matter of fact, even if existing inspection procedures have been consolidated on metallic fractures since the 50s, they need to be improved and modified to assure a full understanding of the phenomena related to composite materials because the capability to find out and to define damage is a necessary step to ensure aircraft integrity and also to evaluate damage reparability and repairing efficiency. Therefore, more and more integration of traditional NDT techniques to apply during production as well as maintenance or first line is due.

For this reason the most modern NDT techniques are designed to be applicable and reliable on composite structures that suffer of different defects and fracture mechanics from metallic structures.

3. DAMAGE OF COMPOSITE MATERIALS

As well known composite materials exhibit a different mechanical behavior from metallic ones. Due to their heterogeneous nature, both static and dynamic structural response can significantly change from metals and hence fracture morphology can show peculiar aspects. If in metallic structure the damage can be classified in certain categories, in composite materials there are further morphologies of damage related to their original technological nature. In table 1 are classified structural damages for material typology. Focusing the attention on composite materials, it can be found three peculiar damage mechanisms: edge damage, delamination and disbanding. The term delamination is used to describe the separation of plies within a laminate. It can be generated from different reasons and can be also non-visible to the naked eye. Delamination can also affect more the one ply through the thickness of the component. Disbonding regards the adhesive interface and it happens when the two surfaces bonded together become partially or completely separated. This kind of defect can be found at skin to honeycomb as well as at stiffener to skin interface. Disbonding is usually non-visible to the naked eye unless it affects an edge or an area wide enough to produce macroscopic surface deformation. Generally, the damage is always a combination of different damages and any kind of these damages would normally require NDT.

Table 1

General material damage		
Scratch	Dent	Puncture
Fatigue/overload crack	Gouge	Heat damage
Fretting	Abrasion	Fastener related damage
Metal damage		
Corrosion	Stress-corrosion crack	Creep
Honeycomb sandwich damage		
Core crushing	Disbonding	
Composite damage		
Edge damage	Delamination (surface, edge or multilevel delamination)	Disbonding

4. NDT TECHNIQUES AND EQUIPMENT APPLICABLE FOR BATTLE DAMAGE ASSESSMENT ON COMPOSITE MATERIALS

The main NDT techniques in use of IAF for composite damage detection and evaluation are:

- ultrasonic (US);
- thermo cameras for classic and lock-in applications (TR);
- radiography (RX);
- shearography;
- mechanical impedance analysis (MIA);
- tap test (TT);
- visual inspection.

The above-mentioned techniques can be realized in a light aircraft-portable version and hence compatible with an ABDR scenario. Although ABDR conditions are usually in first line, wherever possible and practical, the damaged part should be disassembled from the aircraft in order to properly apply the NDT technique.

In order to check NDT equipments functionality and at the same time to calibrate the instruments, NDT reference specimens shall always be used before performing ND evaluation. For special structures a specific reference specimen is usually required. A reference specimen contains known defects, such as scratches, delamination or disbond, usually covering the thicknesses and structural configurations (panels with co-bonded/co-cured stiffener/ribs, honeycomb sandwich structures, etc.) really present on the aircraft (figure 2) and the defects are usually placed at differing depth through the thickness of specimen. Nevertheless for ABDR ND inspections reference specimen application can result very difficult hence defect typology is usually unknown and can change significantly in function of the threat.

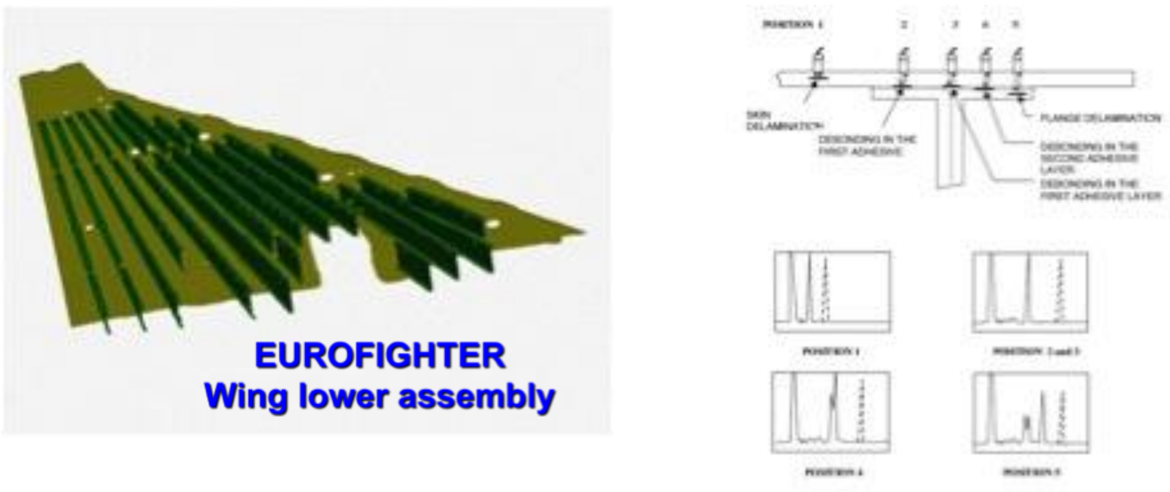


Figure 2

4.1 Ultrasonic

US technique is based on theory of propagation of high frequency mechanical waves through the material. This method is able to detect superficial and internal material discontinuity and it is very efficient when damages are located on a plane parallel to the external surface.
US systems can be applied for inspection of CFRP laminates and CFRP co-bonded structures. In general US systems can work both in transmission and in pulse-echo making the signal acquisition both in amplitude and time of flight (TOF).
With pulse-echo approach US can work applying only one probe on one side of the structure to assess. For this reason, in ABDR context, in order to front time-consuming, pulse-echo approach can be more effective hence applicable avoiding item disassembling applying the probe only on the component external surface. Furthermore, rather than transmission method, pulse-echo technique allows identifying damage location inside material thickness.
US evaluations can be performed from a wide range of equipments and techniques and the choice can depend on several logistic and technical factors, like aircraft location, available equipment, site of damage, etc.
The main advantages/disadvantages of US technique are illustrated in table 2.

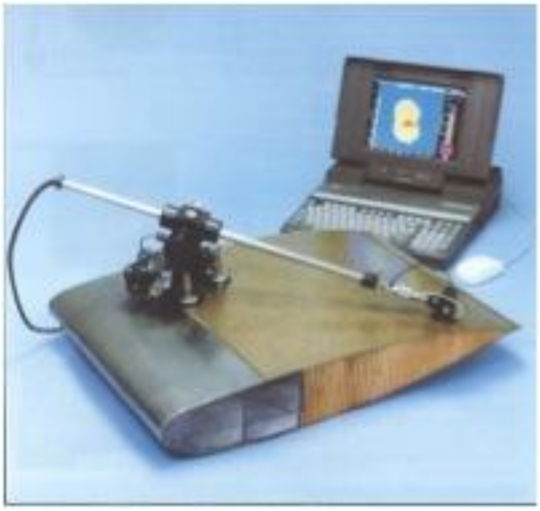
Table 2

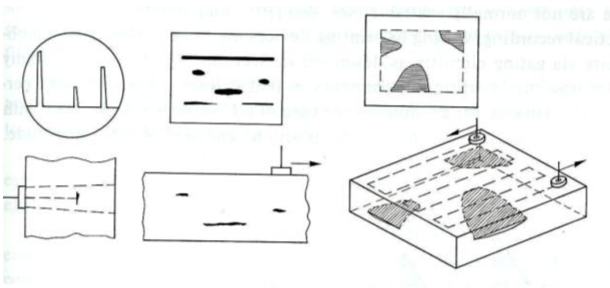
US advantages
Light and portable
Both metals and composite and in general every kind of material
One-surface (pulse-echo) accessible
High sensitivity
High thickness structure
US disadvantages
High training and equipment cost
Low thickness structure, irregular shape, rough, high curvature not investigable
Defects perpendicular to external surface not investigable
Low sensitivity for under surface damages
Necessity of reference specimens

Ultrasonic portable systems (figure 3) consist of:

- Ultrasonic Flaw Detector (UFD);
- probe crystal, with eventually delay, plain contact or appropriate delay probe for thick structures;
- coupling medium;
- reference specimen, covering desired thickness range and structural configuration.

In battle conditions, a manually operated ultrasonic A-scan technique using a portable UFD is quite simply applicable. UFD can also work in automated mode, which enable a C-scan (figure 4), although timing and battle condition as well as damage location may preclude this solution.





A-scan B-scan C-scan

Figure 3

Figure 4

4.2 Thermography

This technique is based on a thermo-camera that measures materials infrared emission when they are heated with a proper artificial light (figure 5).

Figure 5

Use of thermography is increasing more and more, especially during preliminary assessment phase. The reason is because in only few seconds with technique it can be examined great amount of the aircraft structures. Furthermore, thermography works without surface contact that means without disassembling operations and gives an output quickly available without any personnel safety hazards.
The main advantages/disadvantages of thermography technique are illustrated in table 3.

Table 3

TR advantages
Light and portable
Both metals and composite and in general every kind of material
No surface contact
Wide inspection zones
Simple output interpretation
TR disadvantages
High equipment cost
Low sensitivity

4.3 Radiography

RX is one of the first NDT techniques based on the principle that γ and X-rays can pass through the materials that are not transparent at the sunlight. The rays passing through the material print the film at the back-wall creating an image where the dark shapes represent the defects (figure 6).
During the years this technique has been evolved more and more and nowadays the method can detect thickness variations up to 1% of the total thickness.
In figure 7 is shown X-rays equipment made of Coolidge X-rays tube, a transformer and a control panel.
X-ray application in ABDR scenario is fairly complicate because of safety restrictions related to X-ray dispersion. As well known, X-rays are very dangerous for human health and that implies that these tools can be applied only in protected environments, such as screen-wall rooms or spaced out zones with remote control panel. Hence in a front line situation a spaced out zone is required to perform the inspection. X-ray technique can be applied directly on the aircraft structure only if the component is accessible from both external and internal sides.

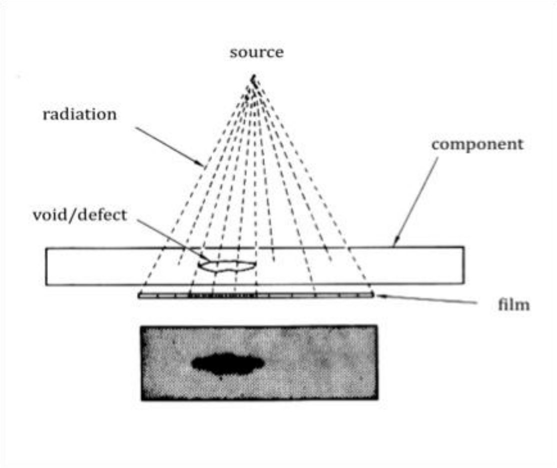


Figure 6

Figure 7

In general, this technique does not detect damages, such as delamination or disbonding of composite materials, which are parallel to the external surfaces. On the other hand, it is very efficient to assess J-spar (figure 8) items integrity. On this kind of structures US probes are not able

to follow the J-stiffener curvature while X-rays can be easily applied (figure 9). RX technique is very reliable also to assess the presence of water into honeycomb structures.

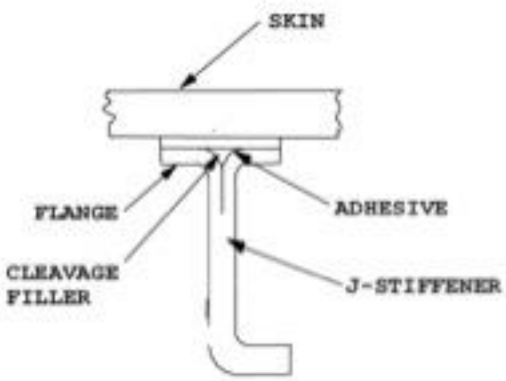


Figure 8

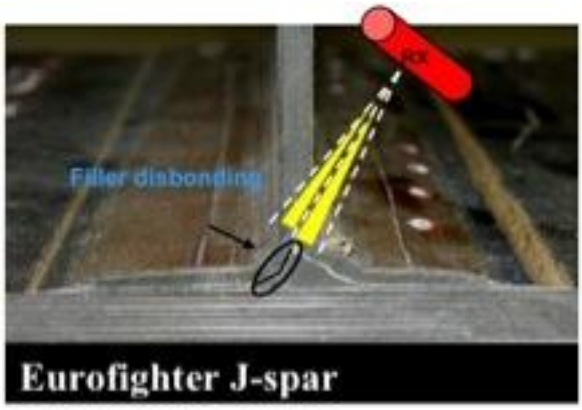


Figure 9

To summarize the main advantages/disadvantages of RX technique are illustrated in table 4.

Table 4

RX advantages
Detect internal defects
Both metals and composite and in general every kind of material
No surface contact
High thickness structure
High sensitivity
Nearly independent on structure shape
RX disadvantages
Necessity of two accessible surfaces
Defects perpendicular to radiation not investigable
Safety systems against radiations
Spaced out inspection zone

4.4 Shearography

Shearography is an interferometric technique using a coherent laser illumination with a few distinct advantages, such as a reduced laser coherence-length, vibration isolation and direct displacement and their derivatives measurement (figure 10). In particular, this technique has a wide application on composite components such as tires and honeycomb structures.
The method performance can be demonstrated by making a comparison between digital shearography and C-scan ultrasonic test on composites. Shearography results particularly effective in fast (1 s) revealing delamination, whilst ultrasonic technique is more time-consuming, as it requires point by point scanning.
Shearography can be successfully applied to evaluate the following configurations:

- adhesive bonding, e.g. pneumatic tires and composite panels;
- flaw and inclusion, e.g. pressure vessels and concrete composite structures;
- leakage detection;
- rotor blade integrity.

The necessity to apply a known stress increment to the component to carry out the test represents the main limit of shearography. For this reason, the development of shearography technology has been focused on innovation of a practical loading methodologies aimed to apply an adequate stress to deform the test piece for the flaws detection. On the other hand, excessive movements may cause speckles de-correlation that results in degradation of fringe quality. In order to reduce this noise, pressurization, partial vacuum, acoustic and thermal shock excitation and mechanical stimulation have been efficiently applied.

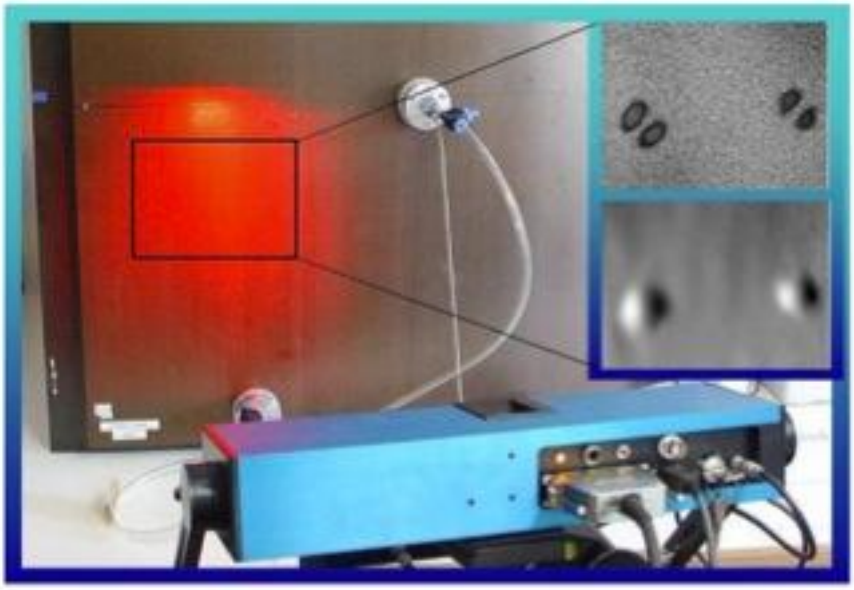


Figure 10

4.5 Tap test

This is a very simple and quick test that can be applied on accessible aircraft composite surfaces to detect the presence of delamination or debonding. Generally tap test can be performed comparing the acoustic response of a known good area with that one of the component under inspection. The sound is produced lightly tapping on their surfaces with a coin or light special hammer (figure 11). In fact the acoustic response of a good part can vary significantly with the presence of a defect. A "flat" or "dead" response is generally considered unacceptable. The entire area under investigation must be tapped and the surface should be dry and free of oil, grease and dirt.
The equipment is portable, but no output data are produced. Test accuracy depends on a subjective interpretation and therefore, only qualified personnel should perform this test.

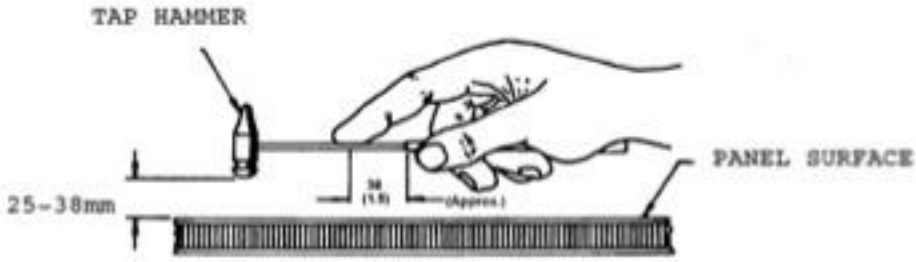


Figure 11

4.6 Mechanical Impedance Analysis (MIA)

MIA is mainly used to investigate bonded structures and it is based on stiffness variations. This method can be considered as an “advanced” Tap Testing because it is basically based on the same physical principles. Although this technique can be applied with every kind of material, it is usually used for composite laminate and honeycomb structures to detect respectively disbonding and core crushing. It is independent on material nature, does not require a coupling medium like US and uses a single transducer for all the applications (figure 12). MIA probes (figure 13) need a little contact surface and they can hence work also on very curved components.

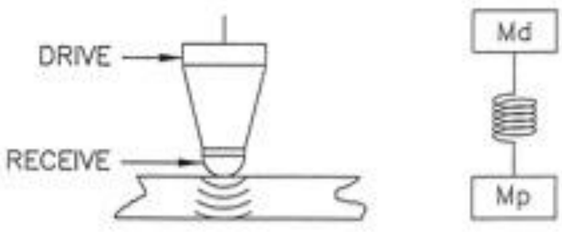


Figure 12

Figure 13

4.7 Visual inspection

Due to his simplicity and versatility this technique can be applied as first assessment to every kind of material. Visual inspections can also be performed through remote optical tools, such as optical fiber endoscope. Endoscope can be connected to light and magnitude systems as well as cameras and PCs. Fiberscope are flexible visual inspection systems with two cables, one to transmit the light and the other one to transmit the image. These systems can also change the optical axis with remote command on the handles and can be really helpful to check engines status and corrosions events.
Nowadays enhanced visual testing techniques are applied in order to visually assess composite

materials integrity. The D-sight technique (figure 14) is usually used to detect low velocity impact damages through the scattering of retroreflective rays. The system is in a box that slides on the surface (figure 15).

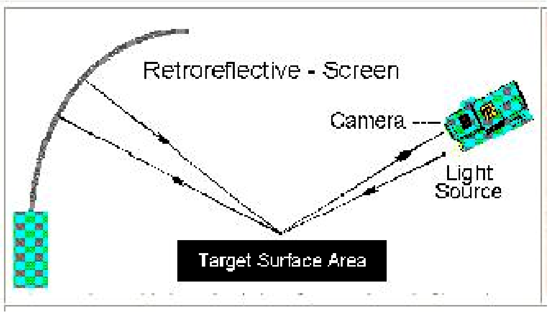


Figure 14

Figure 15

The main advantages/disadvantages of visual inspections technique are illustrated in table 5.

Table 5

Visual inspections advantages
Simplicity
Rapidity
Low cost
Manageable output
Visual inspections disadvantages
Only superficial defects
Low sensitivity
Subjective output data interpretation

5. ND REPAIR ASSESSMENT

If damage exceeds the admissible limit the part can be repaired, if repairing is applicable. NDT techniques play an important role as damage detection but also as repair assessment tool whenever repairing requires, for example, bonding or fastening of damaged items.
The defects that can occur afterwards a repair are usually different from the defects illustrated in table 1. These are related to the repair that is carried out and can be summarized in the following list:

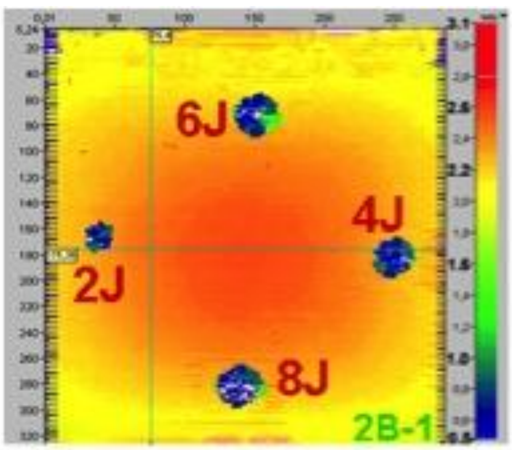
- inter-laminar voids;
- porosity;
- voids;
- unbonding;
- foreign material inclusion.

As for damage assessment phase, whenever the first line conditions allow that, the item should be disassembled from the aircraft before repairing.
Also to evaluate composite laminates repair the most appropriate technique is primarly US. However also radiographic equipment can generate an acceptable output data, giving good definition images of internal structural features such as honeycomb core and adhesive layer and furthermore detecting typical defects in the repair. Unfortunately RX has many logistic obstacles for a first line application.

6. CASE STUDIES

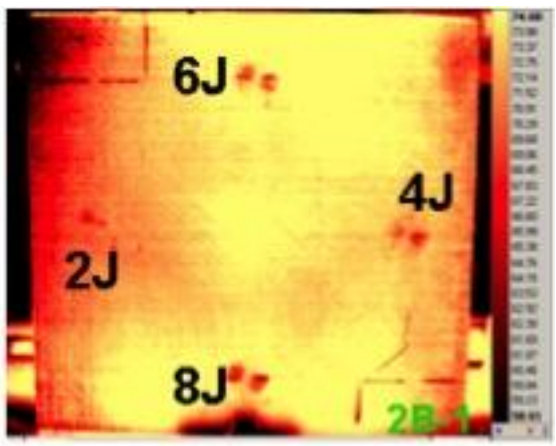
6.1 Low-velocity impact

Beside service experience, studies on composite materials have been carried out at Flight Test Center to improve IAF know-how and enhance IAF NDT capabilities.
In particular, this study is a damage assessment concerned low energy impacts, such as tool droop test, on carbon fiber specimens together with an evaluation of the effectiveness of different ND techniques for damage detection.
The trials have been carried out on 3 mm IM7 laminates made of 16 unidirectional plies $(0/\mp45/90/90/\pm45/0)_s$ and subjected to low velocity impacts ranging between 1-8 J.
Damages evaluation has been performed throughout visual inspection, US, Lock-in TR, MI, and RX techniques.
US tests have been performed using echo-pulse technique with Metalscan Galaxy equipment. An array made of four probes has been applied at frequency of 10 MHz. MI analysis has been conducted with Sonic Bond Master equipment at a frequency of 7.4-8.6 KHz. Gilardoni Radiolight equipment has been used for the RX inspection, analyzing the specimen for 25-30 seconds at 5 mA and 30 KV with the source located at 80 cm. Lock-in termography has been carried out with Cedip Jade III thermo-camera and the images have been elaborated with Altair LI software. In order to perform Lock-in the specimens have been heated with a sinusoidal load at frequency between 0.02 and 1 Hz generated by two 800 W lamps located at 1 m.
In figures 16-19 are illustrated the achieved results showing a comparison between the four techniques outputs. US, MI and TR have been performed on both sides of specimens.



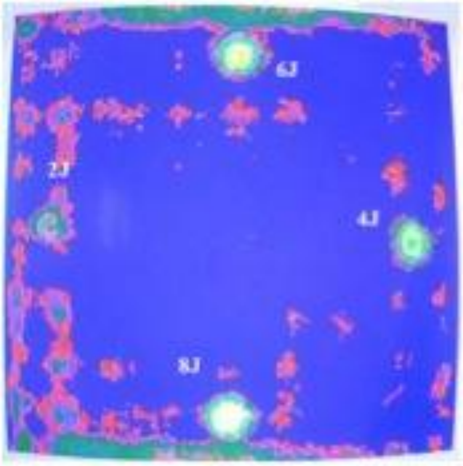
US pulse-echo C-scan map

Figure 16



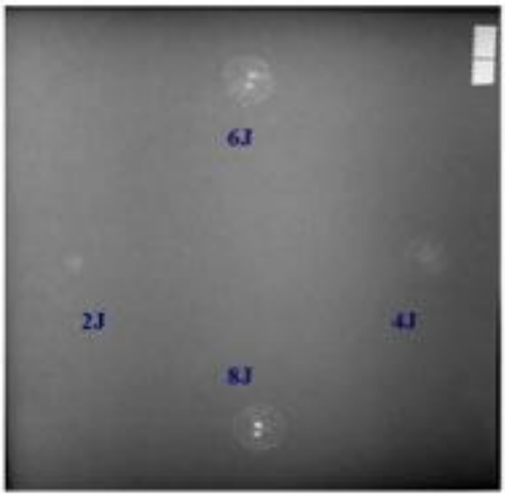
Phase thermal map (0.1 Hz)

Figure 17



MI map

Figure 18



RX image

Figure 19

Visual inspection did not generate any results hence the low velocity impact does not produce damage clearly observable at naked eye, while detection of each delamination occurred between the plies through the specimen thickness is possible by improving the resolution of the thermal map and of ultrasonic C-scan and by focusing the inspection on the impact area (figure 20).

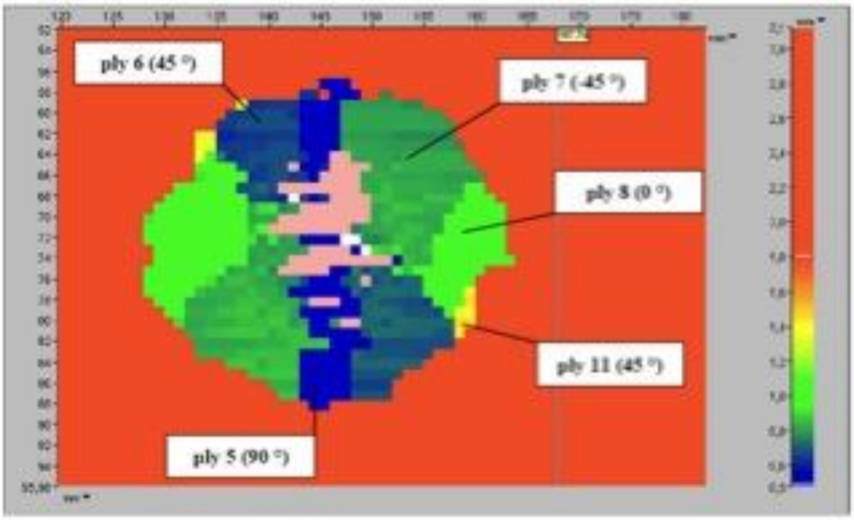


Figure 20

This study makes clear that even very low energy impacts can injury 3 mm thick laminates and not only sandwich structures and this must be taken into account considering particular events like hail, dropped tools, bird-strikes, etc.
About damage detection, as shown by the histograms in figure 21, all applied methods detected the defects, even if in the case of small defects only US and RX techniques exhibited a good sensitivity and reliability. However, TR technique showed good results and the shortest time analysis while, on the contrary, RX resulted the most elaborated and the worst time-consuming approach.

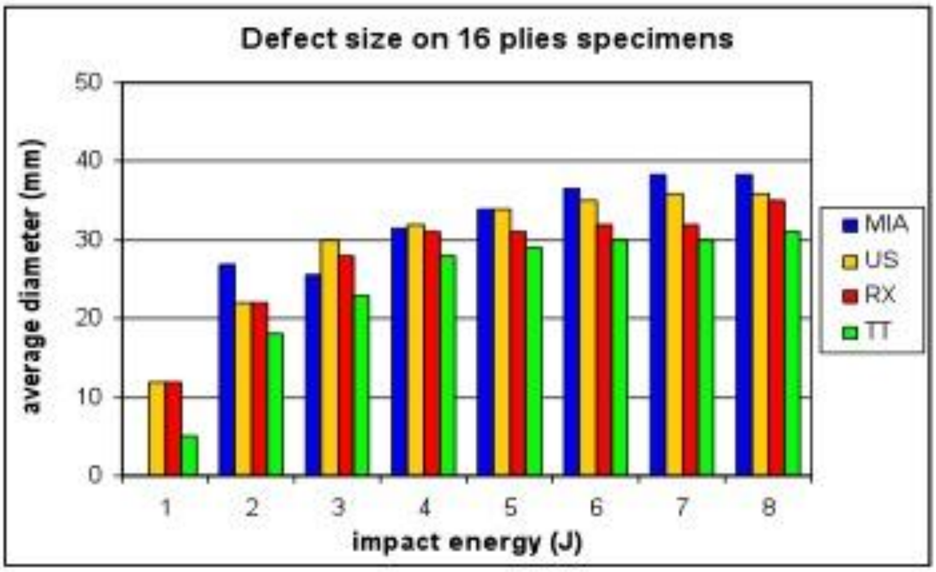
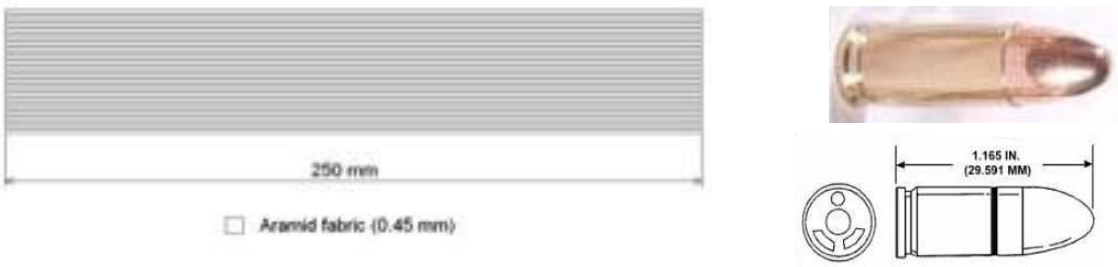


Figure 21

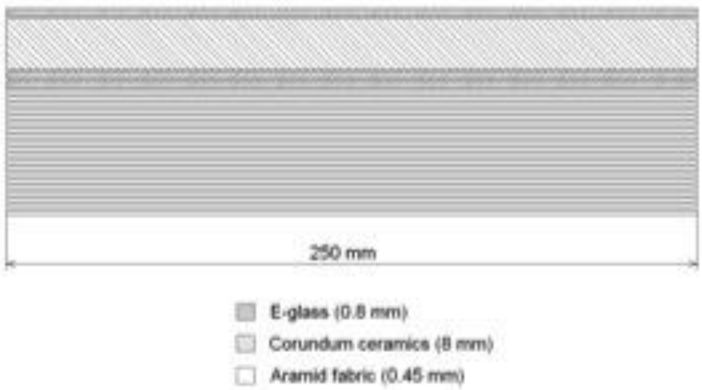
6.2 High-velocity impact

A Technical Group (TG) of Applied Vehicle Technology Panel of NATO Research and Technology Organization is carrying out an experimental study concerning "Materials and Processes for Battle Damage Repair applied on Land and Naval Vehicles" (AVT 155). The TG considered two different threats in order to reproduce real battle damage behavior.
During this activity two different light composite panels made of Kevlar (250x250x10 mm^3) and ceramic/Kevlar (250x250x20 mm^3) (figure 22a and 23a) have been shouted respectively by a 9 mm ball projectile (figure 22b) at striking velocity of 320 m/s and a 7.62 x 51 mm AP NATO projectile (figure 23b) at striking velocity of 830 m/s [12, 13]. The materials used for these panels are typically applied to produce anti-ballistic armors and then are subjeted to battle damages.



a) **b)**

Figure 22



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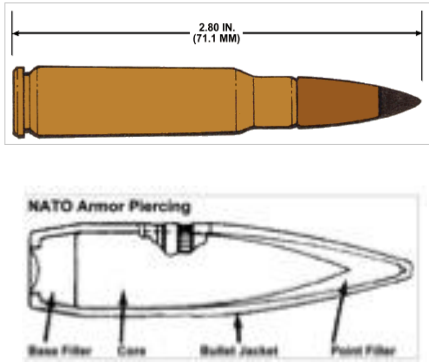
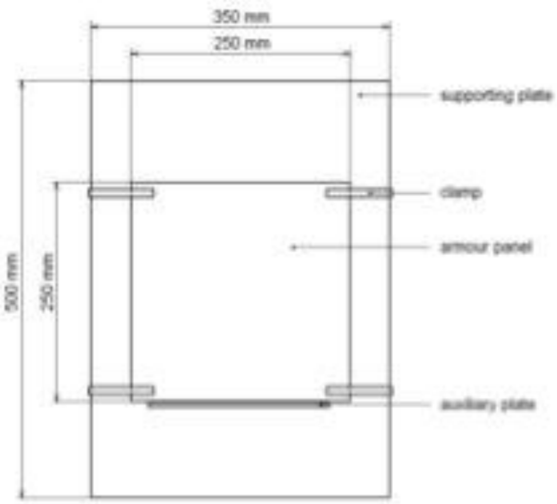


b)

Figure 23

Both armors have been ballistically tested in three different boundary conditions:

- T1: steel backing plate (8x350x500 mm). The target is constrained by four clamps (figure 24a);
- T2: steel backing plate (8x350x500 mm) with a central opening (150x150 mm). The target is constrained by four clamps (figure 24b);
- T3: no backing plate.



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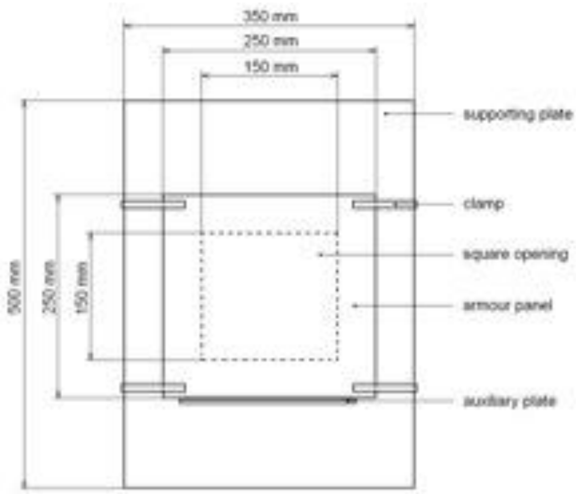


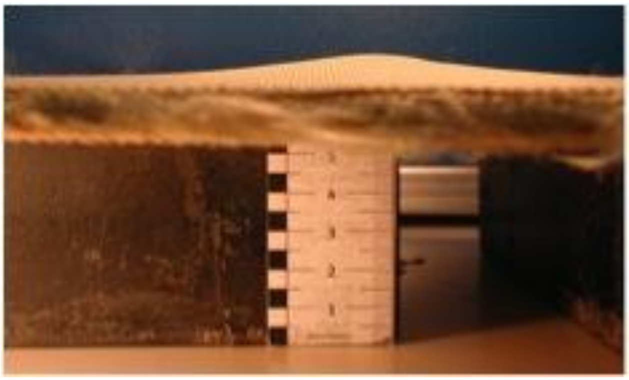
b)

Figure 24

The damages occurred on the panels are showed in figures 25 and 26.

front

back

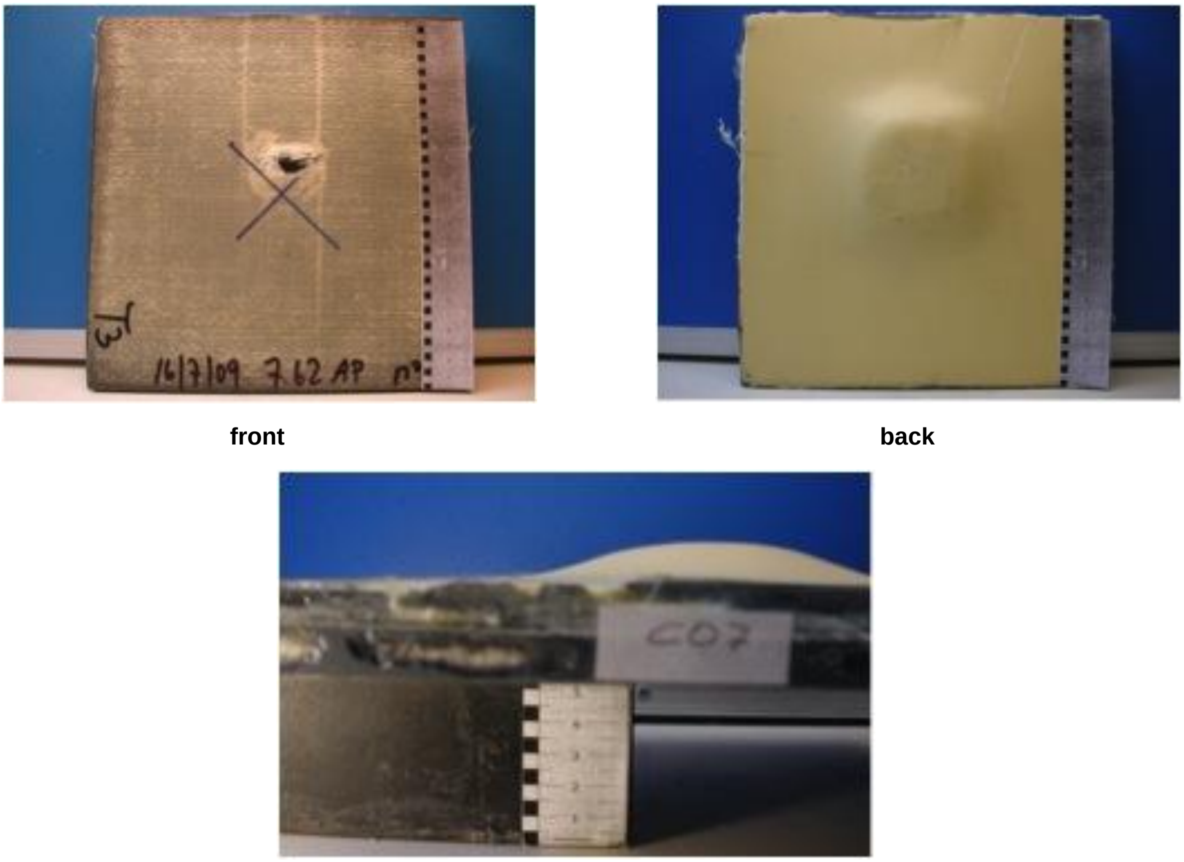


Bulging damage

Figure 25: Kevlar panel (T3 configuration)

All the panels where subjected to ND evaluations with scope to define the delamination area and in order to select the most effective technique for this kind of structures.

First RX inspection has been conducted on both Kevlar and ceramic/Kevlar panels showing that this method did not find out any damages in Kevlar, hence no delamination neither disbonding occurred through the thickness of armors made of Kevlar can be detected with RX. On the contrary RX resulted very effective to reveal cracked ceramic tiles (figure 27). This assessment could be very useful for repairing in order to define the number of tiles to substitute and the extension of the front skin to cut and then to disbond. The white spots represent the material of projectile with high radio-opacity.



front **back**

Bulging damage

Figure 26: ceramic/Kevlar panel (T3 configuration)

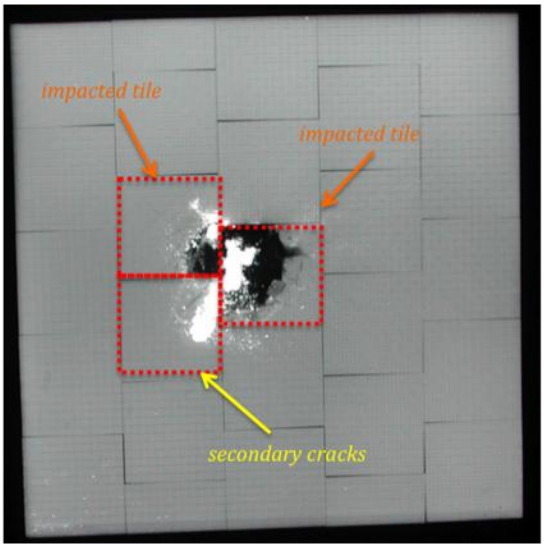


Figure 27

TR controls were also performed to assess the Kevlar post-impact condition. The thermographic control on both front and backing surface of ceramic/Kevlar armors did not give any defect evidence. In fact, in this case damage is likely located at ceramic/Kevlar interface that is, due to armor thickness, too depth to be detectable. On the contrary, lock-in TR inspection performed on Kevlar panels gave reasonable good results, showing the extension of delaminated area (figure 28). The results were particularly acceptable for controls performed on front panel surface. Unfortunately the absence of reference specimens did not permitted to detect delamination depth.

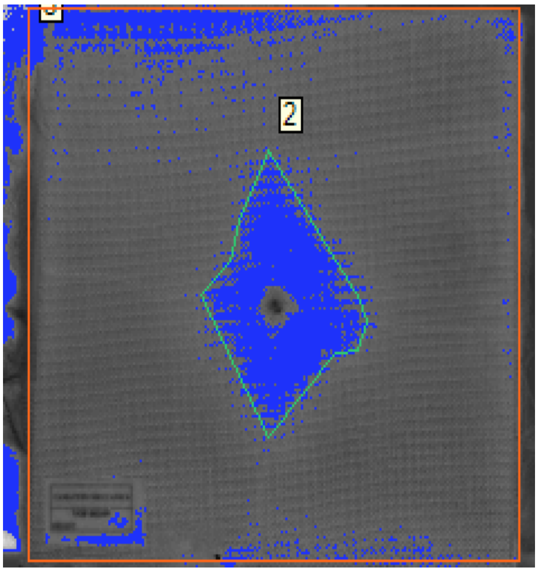


Figure 28

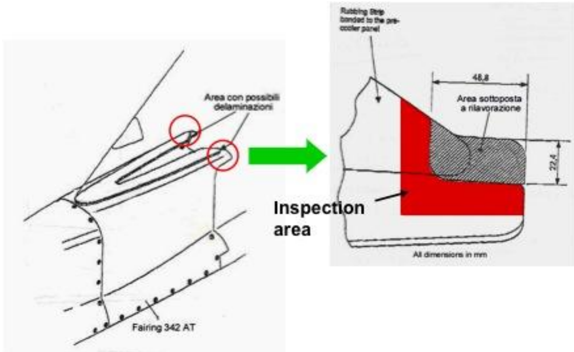
US method resulted inapplicable because both echo-pulse and transmission controls revealed a very low acoustic impedance also with very low frequency and high power probes.

6.3 In-service issues of Eurofigher

At moment the Eurofighter has not scheduled ND inspections on composite structures, although NDT is required in case of battle damage to evaluate the defect and to assess repaired areas.
An example is the edge delamination occurred on the fairing 342 AT (figure 29a), which is subjected to damages (figure 29b) at the rear edges due to insufficient clearance between the pre-cooler panel and the base of the fin. A rework of the rear edges has been established to avoid the problem, that means a cut of the grey area in figure 29c followed by an US inspection (manual pulse-echo with a 5 MHz probe) of the new edge, represented by red area in figure 29c, to ensure absence of any remaining damage. In this case NDT is not used to detect the damage but only to assess the rework/repair effectiveness (figure 30).

a)

b)



c)

Figure 29

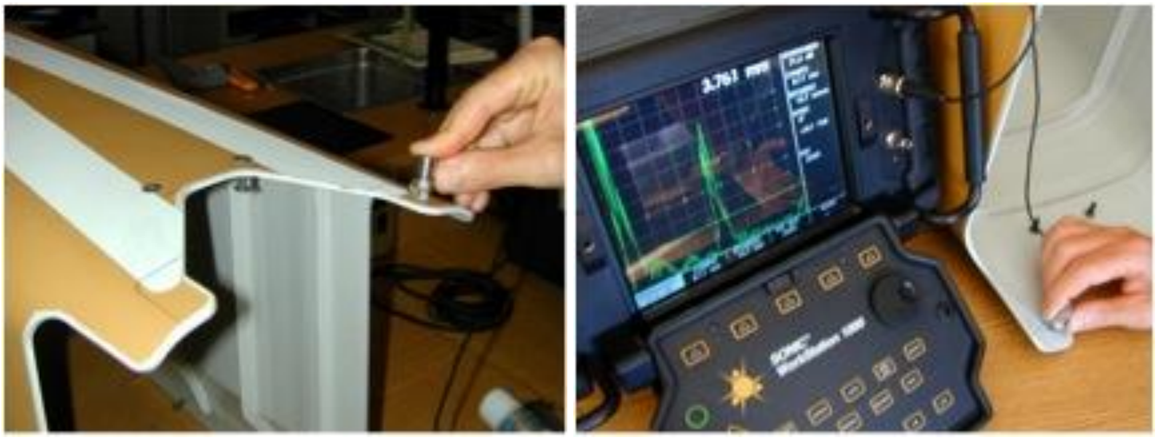


Figure 30

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